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Study of Bose-Einstein Condensation of an Almost Ideal Gas

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13. ABSTRACT *(Maximum 200 words)*

Work by Prof. Ketterle and his collaborators is summarized here

14. SUBJECT TERMS

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Study of Bose-Einstein Condensation of An Almost Ideal Gas

Final Technical Report

At the end of each grant period (generally three years) a final technical report is required. This report must be mailed to a list supplied to you at the beginning of the grant period. It is due no later than 90 days after the end of your grant. You can include it in a renewal proposal, if you are submitting one, to provide the background/progress part of your proposal. The format of this report has been changed, however! An outline of the required format follows:

1. Title of Grant: Study of Bose-Einstein Condensation of An Almost Ideal Gas

2. Principal Investigator: Wolfgang Ketterle

3. R&T Code DURIP, 96PRO6884-00

4. Funding profile:
Indicate the total grant amount and the amount of each yearly increment. If equipment was purchased, indicate the amount spent and a brief description of the equipment.

Total $ 90,500
Equipment: Total equipment purchases $ 90,500.
Argon ion laser ($ 79,000), Wave meter ($11,500).

5. Technical objective:
In bullet format indicate what the goals were of your project. Be concise. More than one objective is OK, but do not exceed three.

The proposal contained the following goals:

- Study of properties of Bose-Einstein condensates of sodium atoms, in particular the observation of collective excitations
- Development of methods to probe the condensate optically and of a magnetic trap to control the shape of the condensate

6. Published papers resulting from this support (numbers only):

a. Submitted but not published 3
b. Published in refereed journals 4
c. Published in non-refereed journals 3

7. Number of technical reports submitted 2 plus 19 conference abstracts

8. Number of books written none

9. Number of book chapters written 1

10. Patents as a result of this work
a. Number of applications filed none
b. Number of patents granted (include patent number and date of patent) none

11. Total number of presentations given about 50

List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

- W. Ketterle, M.R. Andrews, D.S. Durfee, D.M. Kurn, M.-O. Mewes, C.G. Townsend, and N.J. van Druten:
  Bose-Einstein condensation of sodium atoms.
  XXIth International Conference on Low Temperature Physics (LT 21) Aug. 8-14, 1996, Prague, Czech Republic, Conference Handbook, p. 133.

  This was an invited talk at the major international meeting for low temperature physics and demonstrated that the study of ultracold gases has now become a new interdisciplinary field of atomic and condensed matter physics.

- K.B. Davis, M.-O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle:
  Bose-Einstein condensation in a gas of sodium atoms.
  XX International Quantum Electronics Conference IQEC'96, Sydney, Australia, July 14-19, 1996, Technical Digest, p. 28.

  IQEC is the most important international meeting on quantum electronics. In an invited talk, W.K. presented first results on creating two condensates and the rf output coupler. A few months later, this work developed into the realization of an atom laser.

12. Honors and awards received during the granting period:
List individually and include: Source, title, recipient, and date. Underline those that at least in part resulted from your ONR funding.

- 1996 David and Lucile Packard Fellowship (W.K.)
- 1997 I.I. Rabi Prize of the American Physical Society (W.K.)
- 1997 Gustav-Hertz Prize of the German Physical Society (W.K.)
- 1997 JSEP Graduate Fellowship award for Dan M. Kurn
- 7/1997 Promotion to Full Professor with tenure (W.K.)

All these prizes resulted at least in part from ONR funding.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year: none.
Estimate total person-months of post-doc support under this grant: none.

14. Number of different graduate students supported at least 25% of the time for at least one calendar year: none.
Estimate total person-months of graduate student support under this grant: none.

15. List 2 - 5 of the most significant publications resulting from this work:
Include titles and full citations, as well as a few sentences indicating the significance of the publication.

M.R. Andrews, D.M. Kurn, H.-J. Miesner, D.S. Durfee, C.G. Townsend, S. Inouye, and W. Ketterle:
Propagation of sound in a Bose condensate.
Phys. Rev. Lett., in press.

This paper reports the first observation of sound propagation in a Bose condensate and emphasizes similarities with phonons in liquid helium. The measured speed of sound was in agreement with the theory for a weakly interacting Bose gas.

M.-O. Mewes, M.R. Andrews, D.M. Kurn, D.S. Durfee, C.G. Townsend, and W. Ketterle:
Output coupler for Bose-Einstein condensed atoms.
Phys. Rev. Lett. **78**, 582-585 (1997).

In this work, we used rf pulses to couple atoms out of a Bose condensate and observed their propagation. This variable output coupler for a Bose condensate was one step towards the realization of an atom laser.

M.R. Andrews, C.G. Townsend, H.-J. Miesner, D.S. Durfee, D.M. Kurn, and W. Ketterle:
Observation of interference between two Bose condensates.
Science **275**, 637-641 (1997).

This paper was the first direct demonstration of coherence of Bose condensates. It showed that Bose condensates could be released from the magnetic trap and still interfere. This production of coherent atom beams was the realization of a basic atom laser.

16. Major accomplishments:

Here is the meat of what you did! In bullet format indicate the most significant accomplishments for the granting period.

- Realization of an output coupler for Bose-Einstein condensed atoms. This work showed a simple solution to the problem how to build an output coupler for an atom laser.
- Observation of interference between two condensates. This was the first direct evidence for coherence of Bose condensates, and proved the existence of long-range correlations.
- Study of sound propagation in a Bose condensate. We developed a novel way of exciting and observing collective excitation of a Bose condensate. The observation of propagating density perturbations resulted in the first measurement of the speed of sound of a Bose condensate.
- Theoretical work on two-step condensation of an ideal Bose gas. It was shown that Bose gases in highly anisotropic traps condense in two steps. The first step reduces the dimensionality of the motion, and the second step leads to a macroscopic population of the overall ground state.

17. Transitions:

Indicate any results from this grant that has attracted industrial or developmental interest. Indicate the source and form of interest. Give as much detail as possible. Example: SRC provided $100K in funding to determine if the etching process identified in our lab could be utilized by them in a manufacturing environment.

One aspect of our work is the ultimate control over the motion of atoms, at the quantum level. Such precise preparation of atoms might lead to better frequency standards, improved precision experiments and atom lithography with higher resolution. Our techniques are being used in several laboratories around the world, including national labs.

18. Summary of the overall impact of your work in this period.

Give a general statement of the impact of your work in relation to the objectives of the program. Also indicate if this work identified or stimulated a new research area.

The observation of Bose-Einstein condensation has been one of the major goals in atomic physics in the last ten years. This goal has been achieved in 1995 when Bose condensation was observed at JILA and at MIT, and evidence for reaching the quantum degenerate regime was obtained at Rice.

- The study of Bose-condensed gases is rapidly developing into a new subfield interdisciplinary between atomic and condensed matter physics. Quantum degenerate dilute gases have properties which are different from the quantum liquids helium-3 and helium-4. The study of BEC will therefore lead to further insight into macroscopic quantum phenomena.
- A Bose condensate is the ultimate source of ultracold atoms. The kinetic energy of a (released) Bose condensate is on the order of tens of nanokelvin. Such ultracold atoms are ideal for precision experiments (determination of fundamental constants, tests of fundamental symmetries) because the slow motion eliminates most systematic effects. Furthermore, such samples of atoms have potential applications in the field of atom optics, such as the creation of microscopic structures by direct-write lithography or atom microscopy. A Bose condensate may also find applications in metrology, improving frequency standards and atom interferometry.
- Our realization of an atom laser is the first step towards the use of coherent atom beams in atom optics, e.g. in atom interferometry and atom lithography.

19. Four (4) key words/phrases describing your project.

- Degenerate quantum gases
- Bose-Einstein condensation
- Cooling and trapping of neutral atoms
- Atom laser

20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.

1. Demonstration of coherence of Bose-Einstein condensates: The spatial coherence of a Bose condensate was demonstrated by observing interference between two Bose condensates. They were created by evaporatively cooling sodium atoms in a double-well potential formed by magnetic and optical forces. High-contrast matter-wave interference fringes with a period of 15 micrometer were observed after switching off the potential and letting the condensates expand for 40 milliseconds and overlap

2. The MIT atom laser. Pulses of atoms were coupled out of a trapped Bose condensate by using an "rf output coupler". In this scheme, the magnetic moments of the atoms were rotated with an rf pulse, and then the Stern-Gerlach effect split the cloud into trapped

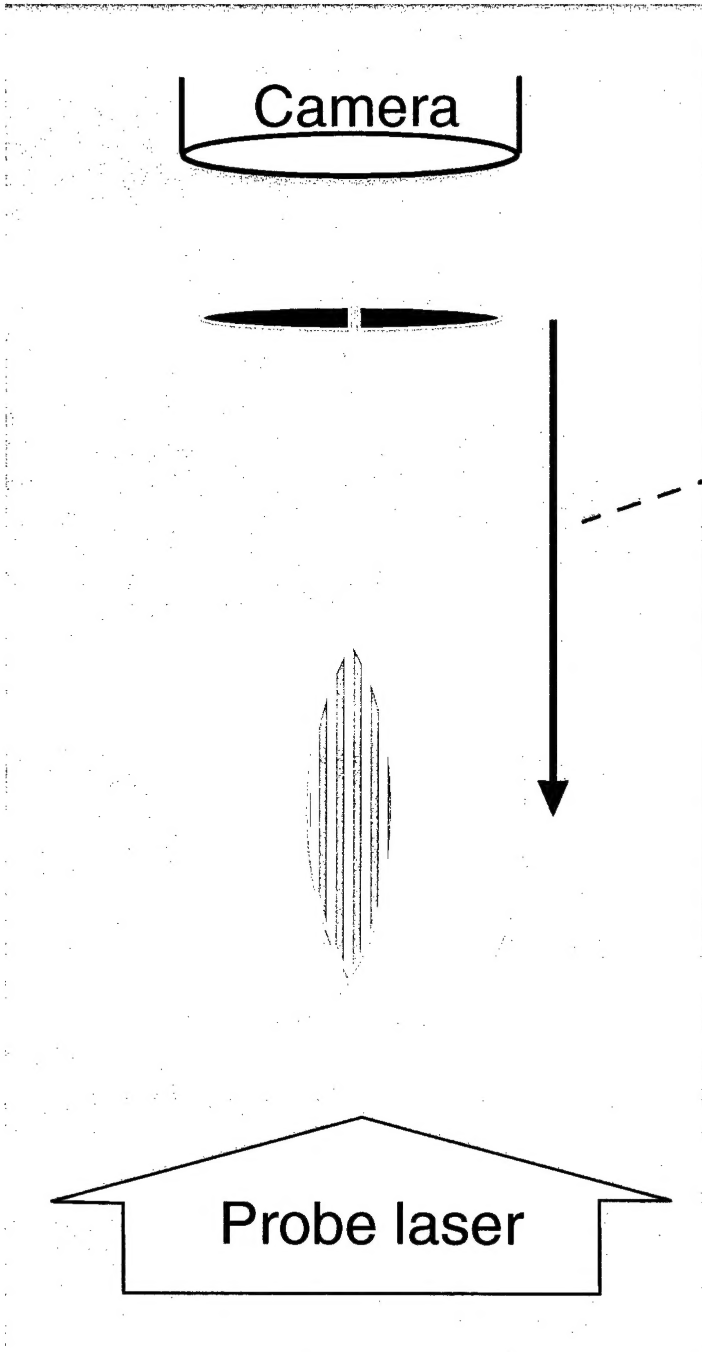
(spin up) and non-trapped (spin down) components. Multiple output pulses could be created by using a sequence of rf pulses.

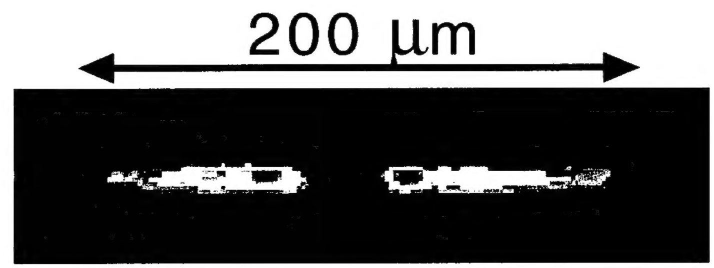
Interference between two outcoupled pulses (coupled out from a split condensate) proved that the rf output coupler preserved the coherence of the condensates. The controlled generation of intense coherent atomic beams was the first realization of a basic atom laser.

3. Experimental setup

The set-up for evaporative cooling from the cloverleaf magnetic trap at MIT. The central (curvature) coils provide axial confinement while the outer coils (the "cloverleaves" or gradient coils) give tight radial confinement. The resulting anisotropic potential gives rise to cigar-shaped clouds. Radio-frequency radiation from an antenna selectively flips the spin of the most energetic atoms, and the remaining atoms rethermalize to a lower temperature. Cooling is forced by lowering the radio-frequency.

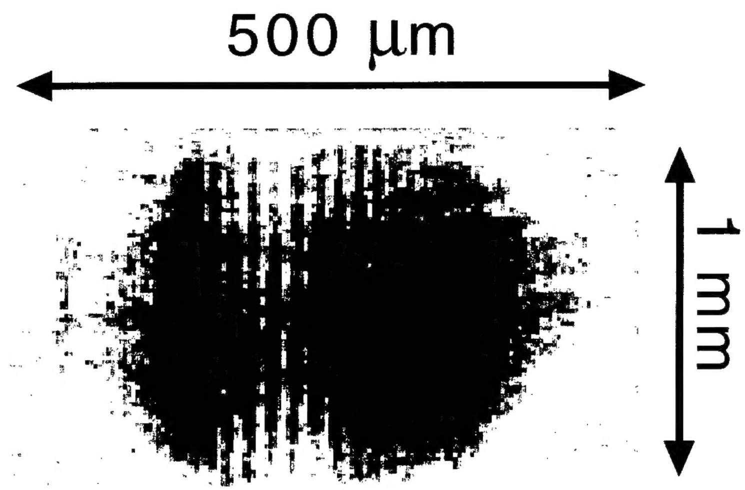
Interference of two condensates





Two trapped condensates

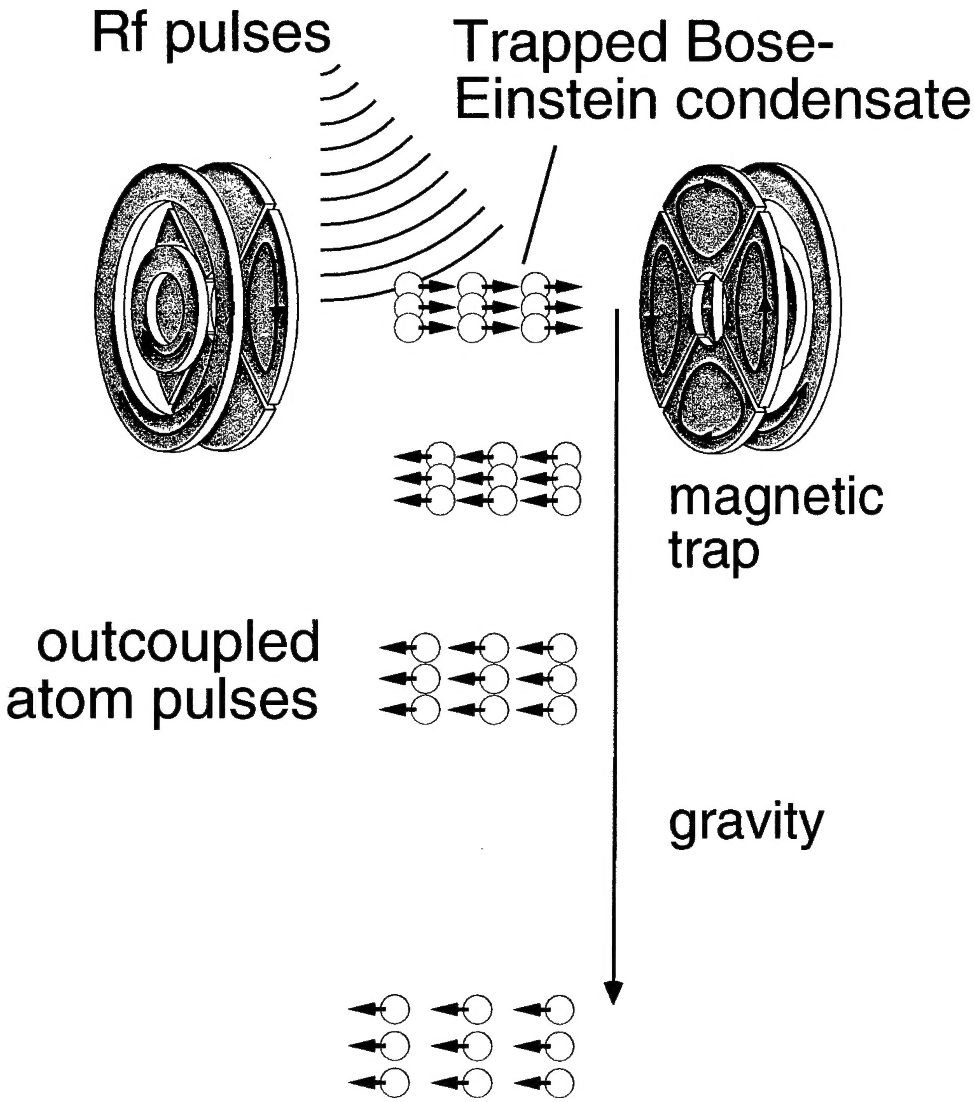
8 mm drop (40 ms) and (anisotropic) expansion



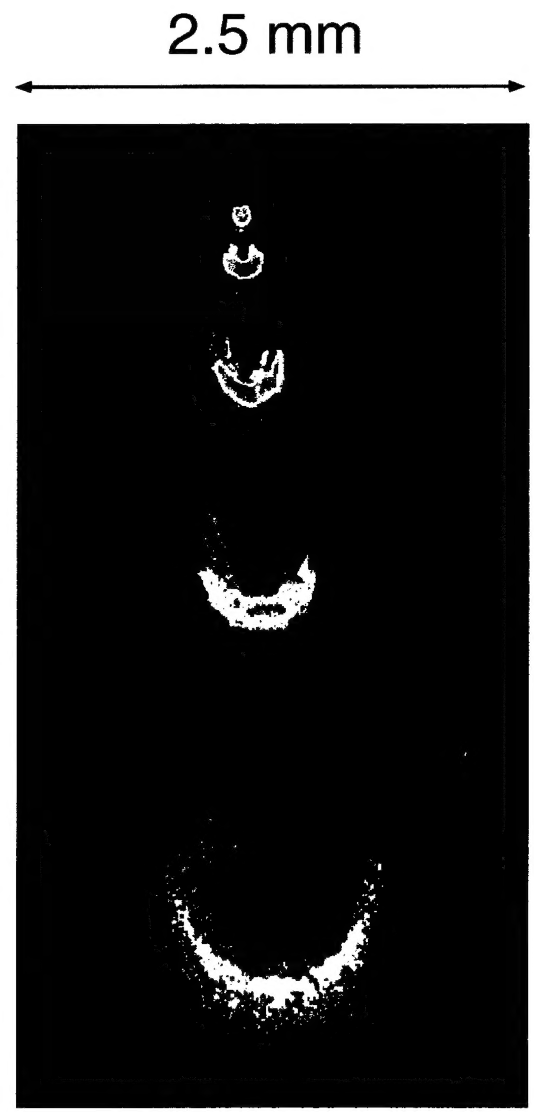
Condensates overlap and interfere

Direct evidence for the coherence of Bose-Einstein condensates

The MIT Atom Laser



5 ms between output pulses



BEC in a "cloverleaf" magnetic trap